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The Reliability of Tensiomyography for Assessment of Muscle Function: A Systematic Review

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THE RELIABILITY OF TENSIOMYOGRAPHY FOR ASSESSMENT OF MUSCLE FUNCTION: A SYSTEMATIC REVIEW

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ABSTRACT

Tensiomyography (TMG) is a non-invasive tool used to assess skeletal muscle tissue, including Displacement (Dm), Contraction Time (Tc), Sustain Time (Ts), Relaxation Time (Tr), and Delay Time (Td). This tool can be used clinically to determine muscular response to exercise. **PURPOSE:** The purpose of this study was to investigate the reliability of TMG measurements. **METHODS:** Studies were identified from multiple databases and evaluated for inclusion. All studies underwent a quality assessment using the Modified Downs and Black checklist for assessing quality studies, and results were extracted from qualified articles. **RESULTS:** 635 studies were identified with 16 studies retained following full article reviews. 12 studies had poor quality, whereas 4 had fair quality. Within-subject reliability was reported in 11 articles, finding good to excellent reliability for all TMG measurements, except Ts and Tr, in 10 articles (CV ranges: Tc: 2.6-9.4, Ts: 5.3-21.3, Tr: 6.4-32.8, Td: 1.16-4.2, Dm: 8.0-14.8). Between-subject reliability was reported in 14 articles, finding fair to excellent reliability for all TMG measurements, except Td, in 12 articles (ICC ranges: Tc: .62-.98, Ts: .71-.95, Tr: .67-.96, Td: .47-.98, Dm: .86-.99). Inter-rater reliability was reported in 2 articles, finding good to excellent reliability for all TMG measurements (ICC ranges: Tc: .92, Ts: .96, Tr: .77, Td: .86, Dm: .96-.97). **DISCUSSION:** Non-invasive TMG has been found to have good to excellent absolute and inter-rater reliability for measuring the properties of skeletal muscles in multiple testing sites. Testing protocols should be taken into consideration including electrode distance, joint angle, and rest time.

Keywords: TMG; skeletal muscle; muscle contractile properties; non-invasive

Abbreviations: electromyography, EMG; mechanomyography, MMG; isokinetic dynamometry, IKD; hand-held dynamometry, HHD; tensiomyography, TMG; displacement, Dm; contraction time, Tc; delay time, Td; contraction velocity, Vc; sustain time, Ts; half-relaxation time, Tr; standard error of measurement, SEM; coefficient of variation, CV; intraclass correlation coefficient, ICC

INTRODUCTION

The biomechanical characteristics of human skeletal muscle have been explored via several methodologies including electromyography (EMG), dynamometry, and mechanomyography (MMG). Among the oldest and most common tools is EMG, a technique used to quantify muscle function based on the measurement of electrical activity at neuromuscular junctions. Surface EMG is non-invasive and involves relatively easy to apply surface electrodes attached to cutaneous tissue of the subject. Fine-wire or needle EMG is a more specific and localized assessment of muscle via the insertion of the electrode into the skin. Difficulty arises when using EMG in clinical practice as it requires technical proficiency for amplification and signal processing. For these reasons, between-day reliability values for EMG typically range from low to high, with fine-wire assessments having lower values[8].

Dynamometry measures the torque production of particular muscle groups through voluntary contraction. Isokinetic dynamometry (IKD) is frequently employed in orthopedic clinical settings as a reliable way to isolate muscle strength across individual joints throughout a given range of motion. This method is useful in that one can determine the speed of motion to obtain a dynamic assessment of muscular force. IKD can be limited, however, due to relative costliness as well as the variability in setup of the machine parts according to the patient's physical characteristics[3,8].

Hand-held dynamometry (HHD) is a portable option that has been found to have moderate validity and reliability compared to IKD[29]. Both methods are limited in that they measure total force production at joints rather than the mechanical properties of individual muscle groups surrounding the joint.

MMG is a widely used technique that employs sensors to detect resting muscle tension, speed of contraction, and radial displacement at the surface of a muscle belly. MMG analysis has typically been characterized by lasers, accelerometers, microphones, and contact sensors that evaluate muscle function followed by involuntary and voluntary stimuli. In the 1990's, however, engineers from Slovenia developed a new MMG sensor that would become the basis for Tensiomyography (TMG), an alternative form of MMG. TMG has been touted to have advantages over other methods due to lower variability of its parameters, relatively simple set up, and streamlined data collection processes. Apart from being easier to use in practice, TMG devices tend to be quite inexpensive and portable, making them ideal for clinical scenarios[7,10]. The TMG sensor is best described as a "spring-loaded probe embedded in a digital displacement sensor". Prior to data collection, the sensor is pushed into the muscle belly at a predetermined pressure level to allow for pre-tension, which can help to improve the consistency of muscle response to stimulation. In addition to using a unique sensor, TMG assessment involves only stimulated, involuntary isometric contractions that are evoked with a single 1 ms-wide biphasic wave. Proprietary computer software uses data from the sensor to produce a twitch curve, from which six primary parameters are determined. In this curve, the y-axis represents muscle displacement in millimeters while the x-axis represents time in milliseconds. The main TMG parameters include displacement (Dm), contraction time (Tc), delay time (Td), contraction velocity (Vc) (Vc=[90%Dm-10%Dm/Tc]), sustain time (Ts), and half-relaxation time (Tr). Displacement (Dm) refers to the peak radial displacement of the muscle and has been attributed to muscle stiffness. Contraction time (Tc) is the time between 10% and 90% of the Dm on the positive slope of the twitch curve. Delay time (Td) is a temporal parameter that measures the time from the initiation of electrical stimulus to when the muscle belly reaches 10% of Dm, or peak displacement. Half-relaxation (Tr) time is the time between when the muscle displacement reaches 90% of max and falls back to 50% of Dm on the negative slope of the curve. Sustain time (Ts) is defined as the time between 50% Dm on both the negative and positive slopes of the curve. Contraction velocity (Vc) is a derived measure that seeks to quantify the rate of muscular contraction. Being that this is a derived measure, authors have used differing methods to calculate Vc. The most common calculation is taking the change in Dm between 10% and 90% and dividing it by Tc. This method is proposed to augment the utility of the Tc parameter and provides a more valid measure of contraction speed by eliminating the influence of Dm, since peak radial displacement values have been found to affect contraction time values simply by nature of the shape of the twitch curve[7,10].

TMG has been reported in a variety of research studies that have focused on a number of variables including, but not limited to, within-subject muscle symmetry, between subject muscle performance, muscular fatigue, and links between TMG parameters and other muscular performance testing. TMG has also been employed as a way to monitor exercise recovery following a bout of power, endurance, and/or multi-day training sessions. With the rising popularity of TMG among clinicians and researchers in regard to muscular assessment, we aim to conduct a systematic review to quantify the reliability of TMG parameters and determine their consistency within and between subjects over time. Due to the variability of inter-stimulus interval, inter-electrode distance, and stimulus amplitude demonstrated across the literature, our secondary aim is to discover the most reliable protocols to help establish a more standardized approach to measurement. We hypothesize that TMG will be found to be reliable as a non-invasive tool for skeletal muscle assessment in healthy individuals.

MATERIALS AND METHODS

Literature Search

An electronic database search from 1990 to 2020 was conducted by two authors, S.M. and D.H., who examined all titles and abstracts to determine initial study eligibility. Relevant studies were identified from PubMed, PEDro, MEDLINE, and Cochrane databases via the search function with independent and combined key words including: Tensiomyography, TMG, Reliability, Validity, Measurement Error. The primary search string is represented by (((“Tensiomyography” OR “TMG” AND “Reliability”)) OR (“Tensiomyography” OR “TMG” AND “Reproducibility”)) OR (“Tensiomyography” OR “TMG” AND “Measurement Error”). Additional studies were found by screening reference lists of previous systematic reviews.

Study Selection

Relevant studies identified through the literature search were assessed for inclusion eligibility by the same two authors. Inclusion criteria included the following elements: a TMG study assessing the reliability of TMG parameters, published in English, published in a peer-reviewed scientific journal between January 1990 and September 2020, and including participants with no significant musculoskeletal conditions. Exclusion criteria including the following elements: TMG assessment process not clearly delineated, reliability of specific TMG parameters not clearly defined, and statistical methods for determining reliability not clearly defined.

Quality Assessment and Best Evidence Synthesis

All studies underwent a quality assessment performed by two authors (S. M. and D. H.) using the Modified Downs and Black checklist for assessing quality studies, and results were extracted from each of the qualified articles. Any disagreements regarding scoring of the quality assessment checklist were resolved via discussion with a third author (W. H.). Table 2 for quality assessment was created in which each study has been given a score for each corresponding subsection of the checklist. Furthermore, the authors, parameters and primary outcomes for each individual study have been outlined in Table 1 for ease of information synthesis.

RESULTS

Search Results

This systematic search yielded a total of 635 articles from the electronic databases employed. Of the 635 articles identified, 16 articles were included in this review based on the inclusion and exclusion criteria as outlined in Figure 1. For TMG reliability testing, this review includes 356 total participants (7.56% female) with study sample sizes ranging from 10 to 64 participants, and ages ranging from 21.3 ± 3.4 years to 38.0 ± 12.0 years. Of the included studies, ten studies had exclusively male participant populations while six studies included female participants. All studies included healthy participants with no acute injury or history of musculoskeletal disease.

Study Types and Measurement Properties

The individual characteristics and primary outcomes of each study are outlined in Table 1. Five of the included studies had an experimental design, with the authors assessing the effects of a given intervention on TMG parameters. The remainder of the studies were observational or descriptive in nature with no intervention given to participants. Twelve studies explored reliability in lower extremity musculature, including gastrocnemius medialis, gastrocnemius lateralis, soleus, vastus lateralis, vastus medialis oblique, rectus femoris, biceps femoris, and semitendinosus. Three studies explored reliability in upper extremity musculature, including biceps brachii, trapezius, deltoideus, and latissimus dorsi. One study explored reliability in the lumbar erector spinae. All studies reported stimulus amplitude, inter-electrode distance, and inter-stimulus interval for TMG assessment.

Quality Assessment Outcomes

The quality of the included studies according to the Modified Downs and Black checklist is reported in Table 2. The Modified Downs and Black checklist was created as a way to reliably examine the quality of randomized and non-randomized research studies, with subscales for reporting, internal validity, external validity and power[35]. This checklist includes 27 total items and a maximum score of 28 points. For interpretation of scoring, each study can be assigned grades of excellent (24-28 points), good (19-23 points), fair (14-18 points), or poor (<14 points)[16]. Twelve out of sixteen studies received an overall grade of poor. The remaining four studies received a grade of fair quality. Lohr et al. and Garcia-Garcia et al. demonstrated the highest quality in the reporting subscale, indicating adequate descriptions of study characteristics and outcomes[5,18]. External validity was found to be insufficient in all studies, except for Rey et al., who identified the population source and the proportion of study participants representative of the population[26]. All studies demonstrated high risk for selection bias as they failed to report recruiting methods, randomization, and participant retention. Furthermore, only two studies reported sufficient power and sample size to detect clinically important effects with an alpha of 0.05.

Reliability Measures

The reliability of TMG parameters Dm, Tc, Ts, Tr, and Td were assessed using different statistical and procedural methods. The most commonly reported reliability measures included standard error of measurement (SEM), coefficient of variation (CV), and intraclass correlation coefficient (ICC). As such, these measures have been reported in this review, where available. Within-subject reliability, or absolute reliability was measured in eleven studies using CV. Within-subject reliability was also measured using SEM in eight studies. Between-subject reliability was reported in fifteen studies through ICC. Furthermore, the included studies examined the reliability of TMG parameters over time and between raters. Inter-day, or between-day reliability was assessed in ten studies. Intra-day reliability was assessed in eight studies. Two studies assessed inter-rater reliability. One study examined the effect of inter-electrode distance on reliability measures. Two studies assessed the reliability of TMG parameters at differing joint angles. And one study assessed the effect of inter-stimulus intervals on reliability measures.

Reliability Outcomes

Coefficient of variation (CV), a well-established measure of absolute or within-subject reliability, has been stated elsewhere to indicate excellent reliability when reported as < 10%[33,36]. In the eleven studies reporting CV, 10 reported good to excellent reliability for Tc, Td, and Dm with ranges as follows: (Tc: 2.6-9.4%, Ts: 5.3-21.3%, Tr: 6.4-32.8%, Td: 1.16-4.2%, Dm: 8.0-14.8%). CV for Tc was found to be excellent in all but 2 studies. CV for Td was found to be excellent in all but 1 study. Excellent CV values for Tr were found in only one study. Five studies reported excellent CV values for Dm in all conditions. Standard error of measurement (SEM), an alternative indicator of within-subject reliability, measures the precision of repeated measures for a single subject. The lower the value for SEM, the more reliable the test[33]. In the eight studies reporting SEM, ranges were as follows: (Tc: 0.25-6.8, Ts: 5.01-29.0, Tr: 1.73-30.0, Td: 0.33-1.52, Dm: 0.19-1.0) TMG parameters Tc, Td, and Dm were found to have the lowest SEM values. Between-subject reliability was reported in fourteen articles using intraclass correlation coefficient (ICC). ICC is considered to be "excellent" when reported as ≥ 0.90, with values closer to 1 indicating better agreement between measures[37]. Poor to excellent between-subject reliability was reported in 12 articles, with ICC ranges were as follows: (Tc: 0.62-0.98, Ts: 0.71-0.96, Tr: 0.62-0.96, Td: 0.47-0.98, Dm: 0.86-0.99). The poorest ICC and CV values for Tc and Dm were reported by Latella et al. and Ditroilo et al. who examined the effect of joint angle on TMG parameters when assessing the biceps brachii and biceps femoris, respectively[5,31]. In the study by Latella et al., reliability of Dm and Tc increased at joint angles of 90 degrees, whereas the study by Ditroilo et al. reported poor reliability for Dm and Tc when measured at 90 degrees[5,31]. All other studies assessing Dm and Tc reported good to excellent ICC values, indicating high between-subject reliability. Inter-rater reliability was reported in 2 articles, finding good to excellent relative reliability for all TMG measurements (ICC ranges: Tc: 0.92, Ts: 0.96, Tr: 0.77, Td: 0.86, Dm: 0.96-0.97). When assessing the effect of inter-stimulus intervals on TMG reliability, Latella et al. reported no significant differences between parameters at 10 second and 20 second intervals[5]. According to Tous-Fajardo et al., increasing the inter-electrode distance from 3 cm to 5 cm, results in a higher Dm value, potentially altering reliability values[33].

DISCUSSION

The purpose of this current study was to perform a systematic review of the literature to investigate the reliability of TMG as a non-invasive assessment tool for properties of skeletal muscle. Our goal was to review all current available research with a more critical appraisal by applying the Modified Downs and Black checklist for assessing quality to each individual study and aggregating all available reliability measures and outcomes into one review. We believe our search strategy exhausted the available evidence for this topic and that our review can be confidently used to assess reliability of TMG as a non-invasive tool for measurement of skeletal muscle in healthy individuals, based on current available evidence. The results of this study were in line with the authors expectations based on the review of the literature conducted prior to the more thorough systematic review.

The first article regarding the use of TMG as an assessment tool was published in 1990 and the earliest article determining reliability of TMG - included in this study - was published in 2008. As a comparison, the earliest published research for EMG as a skeletal muscle assessment tool dates back to 1922 and reliability studies have been exhausted for that particular technology over the last several decades. The results of this systematic review provide support for continued research into the reliability of TMG as an assessment tool for skeletal muscle tissue, however it also highlights the current limitation in available research regarding the reliability of TMG and its clinical utility for patients outside of healthy individuals and trained athletes at this current time, specifically when compared to technology with similar capabilities.

Quality assessment of the 16 articles included in this study resulted in 12 receiving a grade of poor and 4 receiving a grade of fair. The authors found that the majority of articles included in this study lacked the external validity required for good or excellent ratings based on a lack of information in population sourcing, the difficulty with true randomization of participants, and blinding of both participants and raters. For quality to improve in future TMG research, assessors must place an emphasis on sourcing participants who are more representative of the population as a whole and develop true blinded and randomized test protocols for both participants and assessors. The current body of research surrounding TMG leaves for a low applicability to clinical practice based on poor external validity.

Contraction time (Tc) and delay time (Td) variables were found to be the most reliable and half-relaxation time (Tr) was found to be the least reliable, with regards to studies that reported CV. Tc, Td, and Dm values were found to be the most reliable in eight studies that reported SEM. Dm and Tc values were also consistently found to have excellent reliability in studies reporting ICC. This suggests that these parameters should be monitored when assessing for within-subject as well as between-subject changes in muscle contractile properties over time. According to Tous-Fajardo et al. and Paravlic et al., all TMG parameters were found to have good to excellent inter-rater reliability[13,33]. These results are important to note, as it gives evaluators confidence in TMG's reliability to evaluate a single subject across multiple testing times - such as evaluating an athlete across a long-term training program - or multiple subjects at one time - such as evaluating a team of athletes against a targeted measurement.

Further, while most studies used an inter-stimulus interval of ≥ 10 seconds, there were differences in inter-electrode distance, ranging from 3 cm to 10 cm. Tous-Fajardo et al. reported that Dm decreased significantly when decreasing inter-electrode distance from 5 cm to 3 cm. However, there was no difference in reliability reported between the methods[33]. Based on this limited evidence, it is difficult to recommend an ideal inter-electrode distance for maximum reliability, although larger distances may allow for improved motor unit activation and subsequently larger radial displacement curves. According to two studies by Latella et al. and Ditroilo et al., who examined the effect of joint angle on TMG parameters, reliability is also dependent on the resting length of the muscle being assessed[5,31]. While Ditroilo et al. found poor reliability of Tc and Dm when testing the biceps femoris at 90 degrees of knee flexion, Simunic et al., De Paula Simola et al., Piqueras-Sanchiz et al. and Rey et al. found good to excellent reliability of Tc and Dm when testing the biceps femoris at 0, 5, and 30 degrees of knee flexion[4,5,19,24,26]. Therefore it may be advisable to limit knee flexion angles to ≤ 30 degrees when testing lower extremity musculature.. In the upper extremity, Latella et al. reported good to excellent reliability of Tc and Dm when testing the biceps brachii at 90 degrees of elbow flexion versus 45 and 10 degrees[31]. Krizaj et al. also assessed the biceps brachii and reported excellent reliability of Tc and Dm, however the authors did not specify the angle of elbow flexion[34]. Due to the lack of available evidence for testing upper extremity musculature, further studies are needed to determine the best joint angles for reliable TMG assessment.

Similar results were found in previous systematic reviews of TMG reliability. A systematic review conducted by Martin-Rodriguez et al. in 2017 assessed the reliability of TMG parameters by reviewing nine reliability studies.[4] The reliability of Dm, Tc, Td, Tr, and Ts were evaluated in 8 of the 9 studies. 8 of the 9 studies showed excellent ICC value for Dm (0.82-0.99). All studies showed good to excellent ICC value for Tc (0.70-0.99), Ts (0.80-0.96), and Tr (0.77-0.93), and low to excellent ICC value for Td (0.60-0.98). A systematic review and meta-analysis was carried out by Lohr et al. in 2018 to assess the diagnostic accuracy, validity, and reliability of TMG to assess muscle function and fatigue in healthy subjects.[5] This review summarizes the TMG studies that explore accuracy, reliability and validity of TMG parameters Dm, Tc, Td, and Vc with regard to detecting exercise-induced muscle fatigue in healthy male and female subjects. In the meta-analysis, relative reliability values of ICC for Dm, Tc, and Td were found to be 0.98, 0.95, and 0.91 respectively, meaning that all values had excellent relative reliability.

Limitations and Direction for Future Research

As discussed, TMG remains largely new and broad with regards to its use in evaluating skeletal muscle. The main drawback of this systematic review came in the form of limited article inclusion, based on inclusion criteria established prior to the database search, and poor overall quality of the included articles. Moreover, this particular systematic review focused only on TMG measurements for individuals who were healthy and reported no history of orthopedic injury, neuromuscular impairment, cardiovascular conditions, or other health impairment. While TMG can be a reliable assessment tool for this population, more research needs to be done to evaluate its reliability for individuals who have sustained injuries or have other health impairments. This would allow TMG to be used more effectively in clinical practice and in evaluating injured subjects' muscular response to exercise and rehabilitation. We also recognize that results and conclusions of this systematic review are largely based on the interpretations of the authors of the respective studies included. It may be beneficial and appropriate to follow this systematic review with one that includes a meta-analysis of the results in order to have a more robust view of reliability.

CONCLUSION

TMG is found to be a reliable non-invasive assessment tool for evaluating the properties of skeletal muscle in healthy individuals, however more research is needed to evaluate the clinical effectiveness in evaluating skeletal muscle in injured individuals.

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Figures & Tables

Figure 1. An overview of the systematic search strategy and study selection process.

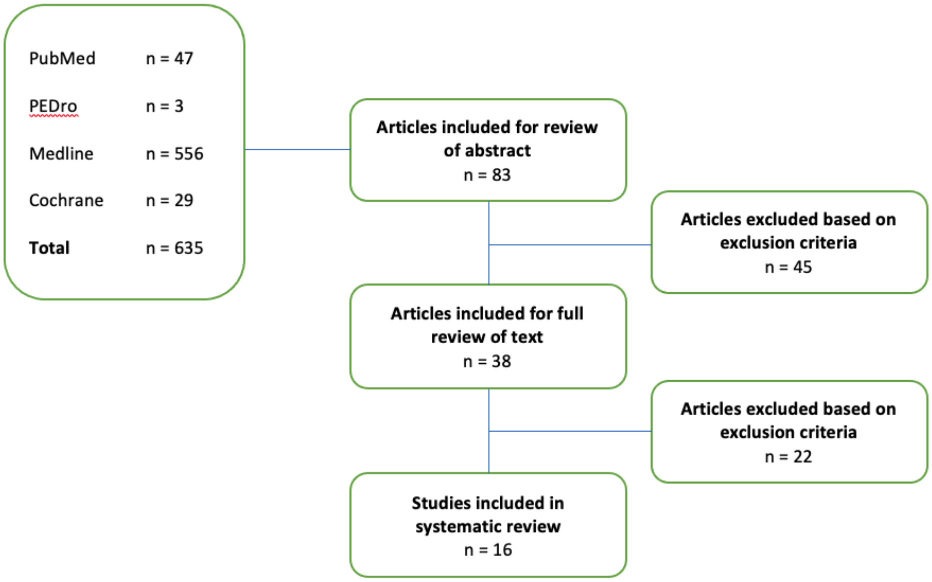
PubMed n = 47
PEDro n = 3
Medline n = 556
Cochrane n = 29
Total n = 635
Articles included for review of abstract n = 83
Articles excluded based on exclusion criteria n = 45
Articles included for full review of text n = 38
Articles excluded based on exclusion criteria n = 22
Studies included in systematic review n = 16

Table 1. Individual Study Characteristics and TMG Reliability Outcomes

Study	Population/ Sample Size	Type of Study	Primary Outcome Measures	Assessment Points, IED, ISI	Muscle Group	Test-Retest Reliability Coefficients/Measurement Error		
Ditroilo et al.[23]	21 healthy male participants Age: 21.3 ± 3.4 years	Crossover Design *Inter-day reliability*	**TMG** Displacement (Dm), Contraction Time (Tc), Sustain Time (Ts), Relaxation Time (Tr), Delay Time (Td) **Reliability** Standard Error of Measurement (SEM), Coefficient of Variation (CV), Intraclass Correlation Coefficient (ICC)	**Session #1** Baseline Post-Warmup Post-MVC Post-Fatigue *Post-4 weeks* **Session #2** Baseline Post-Warmup Post-MVC Post-Fatigue ± 10 cm, 10s	Gastrocnemius Medialis	***CV*** **Tc:** (3.8 - 9.4) **Ts:** (5.3-6.8) **Tr:** (27.8-30.3) **Td:** (7.0-9.2) **Dm:** (8.0-14.8)	***ICC*** **Tc:** (0.62-0.92) **Ts:** (0.71-0.86) **Tr:** (0.67-0.82) **Td:** (0.56-0.62) **Dm:** (0.86-0.95)	***SEM*** **Tc:** (0.61-1.36) **Ts:** (5.59-9.01) **Tr:** (11.73-16.03) **Td:** (1.16-1.52) **Dm:** (0.19-0.30)
Lohr et al.[11]	24 healthy participants (13 female, 11 male) Age: 38.0 ± 12.0 years	Descriptive *Intra-day reliability* *Inter-day reliability*	**TMG** Displacement (Dm), Contraction Time (Tc), Contraction Velocity (Vc) **Reliability** Standard Error of Measurement (SEM), Coefficient of Variation (CV), Intraclass Correlation Coefficient (ICC)	Baseline Post- 3 mins Post- 24 hrs ± 3 cm, 10s	Lumbar Erector Spinae	***ICC*** *Within Day* **Dm**(right): 0.95 **Dm**(left): 0.94 **Tc**(right): 0.88 **Tc**(left): 0.81 **Vc**(right): 0.99 **Vc**(left): 0.99 *Between-Day* **Dm**(right): 0.96 **Dm**(left): 0.96 **Tc**(right): 0.80 **Tc**(left): 0.75 **Vc**(right): 0.97 **Vc**(left): 0.98	***SEM*** *Within-Day* **Dm**(right): 0.54 **Dm**(left): 0.52 **Tc**(right): 1.40 **Tc**(left): 1.72 **Vc**(right): 12.0 **Vc**(left): 10.93 *Between-Day* **Dm**(right): 0.51 **Dm**(left): 0.41 **Tc**(right): 1.91 **Tc**(left): 2.14 **Vc**(right): 19.00 **Vc**(left): 13.17	***CV*** *Within-Day* **Dm**(right): 10.2 **Dm**(left): 12.2 **Tc**(right): 4.4 **Tc**(left): 5.2 **Vc**(right): 4.4 **Vc**(left): 5.2 *Between-Day* **Dm**(right): 12.3 **Dm**(left): 9.7 **Tc**(right): 6.9 **Tc**(left): 7.3 **Vc**(right): 6.9 **Vc**(left): 7.3
Simunic et al.[24]	10 healthy male participants Age: 24.6 ± 3.0	Descriptive *Inter-day reliability*	**TMG** Displacement (Dm), Contraction Time (Tc), Sustain Time (Ts), Relaxation Time (Tr), Delay Time (Td) **Reliability**	Baseline Post- 24 hrs Post- 48 hrs ± 10 cm	Vastus Lateralis, Vastus Medialis Oblique, Biceps Femoris	***ICC*** *VMO* **Td:** 0.94 **Tc:** 0.98 **Ts:** 0.94 **Tr:** 0.88 **Dm:** 0.98 *Vastus Lateralis*	***SEM*** *VMO* **Td:** 0.42 **Tc:** 0.40 **Ts:** 5.46 **Tr:** 1.70 **Dm:** 0.17 *Vastus Lateralis*	***CV*** *VMO* **Td:** 2.8% **Tc:** 2.2% **Ts:** 4.9% **Tr:** 6.4% **Dm:** 4.7% *Vastus Lateralis*

			Standard Error of Measurement (SEM), Coefficient of Variation (CV), Intraclass Correlation Coefficient (ICC)			**Td:** 0.89 **Tc:** 0.98 **Ts:** 0.96 **Tr:** 0.89 **Dm:** 0.99 *Biceps Femoris* **Td:** 0.98 **Tc:** 0.98 **Ts:** 0.95 **Tr:** 0.89 **Dm:** 0.99	**Td:** 0.30 **Tc:** 0.25 **Ts:** 4.99 **Tr:** 3.18 **Dm:** 0.25 *Biceps Femoris* **Td:** 0.40 **Tc:** 1.06 **Ts:** 5.01 **Tr:** 4.12 **Dm:** 0.43	**Td:** 1.8% **Tc:** 1.5% **Ts:** 4.4% **Tr:** 7.6% **Dm:** 4.7% *Biceps Femoris* **Td:** 2.6% **Tc:** 4.9% **Ts:** 3.3.% **Tr:** 9.3% **Dm:** 4.2%
Krizaj et al.[34]	13 healthy male participants Age: 30.7 ± 7.4 years	Descriptive *Intra-day reliability*	**<u>TMG</u>** Displacement (Dm), Contraction Time (Tc), Sustain Time (Ts), Relaxation Time (Tr), Delay Time (Td) **<u>Reliability</u>** Intraclass Correlation Coefficient (ICC)	30 measurements for each subject within 5 minutes ± 10 cm, 10s	Biceps Brachii	***ICC*** **Dm:** 0.98 **Td:** 0.94 **Tc:** 0.97 **Ts:** 0.89 **Tr:** 0.86		
Tous-Fajardo et al.[33]	18 healthy male participants Age: 22.9 ± 3.8 years	Descriptive *Inter-rater reliability* *Intra-day reliability* *Inter-electrode distance reliability*	**<u>TMG</u>** Displacement (Dm), Contraction Time (Tc), Sustain Time (Ts), Relaxation Time (Tr), Delay Time (Td) **<u>Reliability</u>** Standard Error of Measurement (SEM), Coefficient of Variation (CV), Intraclass Correlation Coefficient (ICC)	4 tests for each subject separated by 3 min rest periods ± 3 and ± 5 cm, ≥ 10s	Vastus Medialis Oblique	*Inter-rater reliability* ***ICC*** **Dm:** 0.97 **Tc:** 0.92 **Td:** 0.86 **Tr:** 0.77 **Ts:** 0.96 ***CV*** **Dm:** 4.7% **Tc:** 3.4% **Td:** 2.7% **Tr:** 14.2% **Ts:** 2.4% ***SEM*** **Dm:** 0.3 **Tc:** 0.9 **Td:** 0.9 **Tr:** 18.3 **Ts:** 7.2	*Inter-electrode distance reliability (5cm vs. 3cm)* ***ICC*** **Dm:** 0.97 **Tc:** 0.84 **Td:** 0.85 **Tr:** 0.62 **Ts:** 0.94 ***CV*** **Dm:** 6.7% **Tc:** 4.5% **Td:** 2.0% **Tr:** 17.6% **Ts:** 4.4% ***SEM*** **Dm:** 0.3 **Tc:** 1.3 **Td:** 0.7 **Tr:** 30.0 **Ts:** 9.2	

Latella et al.[6]	15 healthy participants (13 male, 2 female) Age: 29.5 ± 7.4 years	Descriptive *Inter-day reliability* *Joint angle reliability* *Rest interval reliability*	**TMG** Displacement (Dm), Contraction Time (Tc), Sustain Time (Ts), Relaxation Time (Tr), Delay Time (Td) **Reliability** Intraclass Correlation Coefficient (ICC), Standard Error of the Mean (SEM), Coefficient of Variation (CV)	2 blocks of 5 stimuli separated by 2 mins delivered at each joint angle (10, 45, 90) 2 days of measurement separated by ≥ 48 hours ± 5 cm, 10s or 20s	Biceps Brachii	***ICC*** **Td:** 10s-20s 10* (0.88-0.94) 45* (0.76-0.84) 90* (0.47-0.50) **Tc:** 10s-20s 10* (0.79-0.66) 45* (0.73-0.45) 90* (0.75-0.83) **Ts:** 10s-20s 10* (0.72-0.75) 45* (0.91-0.92) 90* (0.90-0.88) **Tr:** 10s-20s 10* (0.90-0.94) 45* (0.96-0.92) 90* (0.93-0.84) **Dm:** 10s-20s 10* (0.65-0.76) 45* (0.89-0.86) 90* (0.84-0.90)	***CV*** **Td:** 10s-20s 10* (2.09-2.35%) 45* (2.47-2.67%) 90* (2.98-2.15%) **Tc:** 10s-20s 10* (4.41-5.72%) 45* (6.49-7.72%) 90* (7.32-7.03%) **Ts:** 10s-20s 10* (6.89-6.24%) 45* (6.91-6.27%) 90* (6.42-5.50%) **Tr:** 10s-20s 10* (14.28-12.05%) 45* (12.57-10.97%) 90* (9.97-15.26%) **Dm:** 10s-20s 10* (13.06-5.81%) 45* (8.57-8.62%) 90* (8.65-5.81%)	***SEM*** **Td:** 10s-20s 10* (0.39-0.58) 45* (0.51-0.68) 90* (1.19-1.18) **Tc:** 10s-20s 10* (1.22-1.65) 45* (1.75-2.90) 90* (2.25-1.80) **Ts:** 10s-20s 10* (14.67-13.8) 45* (10.77-9.590 90* (9.60-9.79) **Tr:** 10s-20s 10* (12.65-9.33) 45* (10.14-12.96) 90* (9.59-14.04) **Dm:** 10-20s 10* (1.28-1.12) 45* (1.14-1.28) 90* (1.31-1.02)
Paravlic et al.[13]	18 healthy participants (10 males, 8 females) Age: 30.3 ± 10.3 years	Descriptive *Intra-day reliability* *Inter-day reliability* *Inter-rater reliability*	**TMG** Displacement (Dm) **Reliability** Intraclass Correlation Coefficient (ICC), Standard Error of Measurement (SEM), Coefficient of Variation (CV)	Baseline Post- 24 hrs Post- 48 hrs ± 4 cm, 10s	Soleus	***ICC*** *Intra-rater* **Dm:** 0.97 *Between-day* **Dm:** 0.88 *Inter-rater* **Dm:** 0.96	***SEM*** *Intra-rater* **Dm:** 0.63 *Between-day* **Dm:** 0.93 *Inter-rater* **Dm:** 0.50	***CV*** *Intra-rater* **Dm:** 7.5 *Between-day* **Dm:** 10.5 *Inter-rater* **Dm:** 8.5
Piqueras-Sanchiz et al.[1]	36 healthy male participants Age: 24.8 ± 5.8 years	Descriptive Cross-Sectional *Intra-day reliability*	**TMG** Displacement (Dm), Contraction Time (Tc), Contraction Velocity (Vc), Sustain Time (Ts), Relaxation Time (Tr), Delay Time (Td) **Reliability** Intraclass Correlation Coefficient (ICC), Standard Error of Measurement (SEM), Coefficient of Variation (CV)	6 conditions, 36 measurements per participant separated, 18 per muscle ± 5 cm, ≥ 60s	Vastus Medialis Oblique, Rectus Femoris	*Vastus Medialis Oblique* ***ICC*** **Dm:** (0.95-0.97) **Tc:** (0.95-0.97) **Td:** (0.85-0.93) **Tr:** (0.76-0.89) **Ts:** (0.88-0.92) ***CV*** **Dm:** (2.9-3.8) **Tc:** (1.6-2.4) **Td:** (1.6-2.3) **Tr:** (23.1-38.1) **Ts:** (4.4-6.2)	*Rectus Femoris* ***ICC*** **Dm:** 0.98 **Tc:** (0.97-0.99) **Td:** (0.93-0.96) **Tr:** (0.82-0.96) **Ts:** (0.83-0.96) ***CV*** **Dm:** (2.9-4.2) **Tc:** (2.4-3.0) **Td:** (1.8-2.7) **Tr:** (18.8-40.9) **Ts:** (12.7-22.9)	

						SEM **Dm:** (0.24-0.31) **Tc:** (0.25-0.49) **Td:** (0.33-0.50) **Tr:** (19.62-23.69) **Ts:** (8.10-10.61)	***SEM*** **Dm:** (0.28-0.35) **Tc:** (0.45-0.87) **Td:** (0.40-0.53) **Tr:** (12.0-28.75) **Ts:** (12.54-26.90)
Piqueras-Sanchiz et al.[4]	30 healthy male participants Age: 24.4 ± 3.4 years	Repeated measures experiment *Inter-day reliability*	**<u>TMG</u>** Displacement (Dm), Contraction Time (Tc) **<u>Reliability</u>** Intraclass Correlation Coefficient (ICC)	Baseline Post-Exercise Protocol Post- 24 hrs. Post- 48 hrs. Post- 72 hrs. ± 10 cm, 15s	Biceps Femoris, Semitendinosus	***ICC*** **Dm:** (0.96-0.99) **Tc:** (0.97-0.99)	
Wilson et. al.[9]	21 healthy participants (15 male, 6 female) Age: 27.0 ± 5.6 years	Within subject, repeated measure study *Intra-day reliability*	**<u>TMG</u>** Displacement (Dm) **<u>Reliability</u>** Intraclass Correlation Coefficient (ICC), Coefficient of Variance (CV)	Baseline Post- 3 min Post- 6 min ± 5 cm, 60s	Rectus femoris	***CV:*** *5.7%* ***ICC:*** *0.92*	
Garcia-Garcia et al.[18]	21 participants (4 male, 17 female) Age: 22.8 ± 6.7 years	Cohort *Intra-day reliability*	**<u>TMG</u>** Displacement (Dm), Contraction Time (Tc), Sustain Time (Ts), Relaxation Time (Tr), Delay Time (Td) **<u>Reliability</u>** Intraclass Correlation Coefficient (ICC)	2 measurements in one muscle from each participant with a 10-15 minute interval between measurements ± 10 cm, 10s	Trapezius, Deltoideus, Latissimus dorsi	***ICC*** **Dm:** 0.96 **Tc:** 0.94 **Ts:** 0.94 **Td:** 0.83 **Tr:** 0.80	
Ditroilo et al.[31]	16 healthy participants (14 male, 2 female) Age: 23.4 ± 4.9 years 10 were part of reliability portion	Descriptive *Inter-day reliability*	**<u>TMG</u>** Displacement (Dm), Contraction Time (Tc)	Baseline Post- 48 hrs. 1 measurement per joint angle (0,45,90) ±10 cm, 10 s	Biceps Femoris	***ICC*** **Dm:** 0* (0.82) 45* (0.57) 90* (-0.57) **Tc:** 0* (0.82) 45* (0.62) 90* (-0.42)	***CV*** **Dm:** 0* (19.8%) 45* (19.7%) 90* (43.1%) **Tc:** 0* (3.6%) 45* (3.7%) 90* (3.9%)

<table>
<tr><td>Rey et al.[26]</td><td>78 professional male soccer players
Age: 26.6 ± 4.4 years

15 were part of reliability portion</td><td>Descriptive

Intra-day reliability</td><td><u>TMG</u>
Displacement (Dm), Contraction Time (Tc), Sustain Time (Ts), Relaxation Time (Tr), Delay Time (Td)
<u>Reliability</u>
Intraclass Correlation Coefficient (ICC)</td><td>2 measurements in each muscle per participant
± 10-12 cm, 10s</td><td>Rectus Femoris, Biceps Femoris</td><td colspan="3">ICC
Dm: 0.95
Tc: 0.86
Td: 0.82
Tr: 0.78
Ts: 0.94</td></tr>
<tr><td>Pareja-Blanco et al.[2]</td><td>64 resistance-trained males
Age: 24.1 ± 4.3 years</td><td>Longitudinal Experimental

Inter-day reliability</td><td><u>TMG</u>
Displacement (Dm), Contraction Time (Tc), Delay Time (Td)
<u>Reliability</u>
Coefficient of Variation (CV)</td><td>72 hrs. pre-training
72 hrs. post-training (8 weeks)

± 5 cm, 10s</td><td>Vastus Medialis Oblique, Vastus Lateralis</td><td colspan="3">CV
Vastus Medialis Oblique
Dm: 5.5%
Tc: 2.6%
Td: 3.1%
Vastus Lateralis
Dm: 5.0%
Tc: 3.4%
Td: 3.0%</td></tr>
<tr><td>Carrasco et al.[32]</td><td>20 healthy male participants
Age: 24.16 ± 0.62</td><td>Experimental

Inter-day reliability</td><td><u>TMG</u>
Displacement (Dm), Contraction Time (Tc), Sustain Time (Ts), Relaxation Time (Tr), Delay Time (Td)
<u>Reliability</u>
Intraclass Correlation Coefficient (ICC)</td><td>Baseline
Post-intense exercise (48 hrs.)
Post-recovery period (15 mins)

± 10 cm, 15s</td><td>Rectus Femoris</td><td colspan="3">ICC
Dm: 0.92
Tc: 0.83
Td: 0.89
Tr: 0.88
Ts: 0.90</td></tr>
<tr><td>De Paula Simola et. al.[19]</td><td>20 healthy male sport students
Age: 26.5 ± 6.7 years</td><td>Experimental

Inter-day reliability</td><td><u>TMG</u>
Displacement (Dm), Contraction Time (Tc), Sustain Time (Ts), Relaxation Time (Tr), Delay Time (Td)
<u>Reliability</u>
Intraclass Correlation Coefficient (ICC), Standard Error of the Mean (SEM), Coefficient of Variation (CV)</td><td>Baseline
24 hrs. post-5-week training intervention

± 10 cm, 10s</td><td>Rectus Femoris, Biceps Femoris Gastrocnemius Lateralis</td><td>SEM
Rectus Femoris
Tc: 1.9
Td: 1.2
Tr: 26.9
Dm: 1.0
Ts: 29.0
Biceps Femoris
Tc: 5.6
Td: .8
Tr: 22.1
Dm: .9
Ts: 13.3
Gastrocnemius Lateralis
Tc: 6.8
Td: 1.3
Tr: 8.1</td><td>CV
Rectus Femoris
Tc: 4.9%
Td: 3.8%
Tr: 32.8%
Dm: 9.3%
Ts: 21.3%
Biceps Femoris
Tc: 8.7%
Td: 2.4%
Tr: 20.6%
Dm: 10.4%
Ts: 4.9%
Gastrocnemius Lateralis
Tc: 8.5%
Td: 4.2%
Tr: 12.6%</td><td>ICC
Rectus Femoris
Tc: 0.94
Td: 0.87
Tr: 0.86
Dm: 0.92
Ts: 0.85
Biceps Femoris
Tc: 0.91
Td: 0.92
Tr: 0.70
Dm: 0.95
Ts: 0.88
Gastrocnemius Lateralis
Tc: 0.93
Td: 0.90
Tr: 0.93</td></tr>
</table>

						Dm: 0.9 **Ts:** 21.6	**Dm:** 13.7% **Ts:** 8.5%	**Dm:** 0.94 **Ts:** 0.87

**IED = Inter-electrode distance, * ISI = Inter-stimulus interval, *VMO = Vastus Medialis Oblique.*

Table 2. Quality Assessment of Included Studies – Modified Downs and Black Checklist

Questions	**Ditroilo et al.[23]** 11/28	**Lohr et al.[11]** 17/28	**Simunic et al.[24]** 12/28	**Krizaj et al.[34]** 10/28	**Tous-Fajardo et al.[33]** 12/28	**Latella et al.[6]** 12/28	**Paravlic et al.[13]** 13/28	**Piqueras-Sanchiz et al.[1]** 12/28	**Piqueras-Sanchiz et al.[4]** 12/28	**Wilson et al.[9]** 13/28	**Garcia-Garcia et al.[18]** 18/28	**Ditroilo et al.[31]** 11/28	**Rey et al.[26]** 16/28	**Pareja-Blanco et al.[2]** 15/28	**Carrasco et al.[32]** 12/28	**De Paula Simola et al.[19]** 13/28
Reporting																
Item #1	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Item #2	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Item #3	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Item #4	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Item #5	No	Yes	No	No	No	No	No	No	No	No	Yes	No	No	No	No	No
Item #6	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Item #7	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Item #8	No	No	No	No	No	No	No	No	No	No	Yes	No	No	No	No	No
Item #9	No	Yes	No	No	No	No	No	No	No	No	No	No	No	No	No	No
Item #10	No	No	Yes	No	No	Yes	Yes	No	Yes	No	Yes	No	Yes	Yes	Yes	Yes
External Validity																
Item #11	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Yes	Yes	Yes	N/A	N/A	N/A
Item #12	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Yes	N/A	Yes	N/A	N/A	N/A

Item #13	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Internal Validity - bias																
Item #14	No	No	N/A	No	No	No	No	No	No	Yes	No	N/A	N/A	N/A	No	No
Item #15	No	No	N/A	No	Yes	No	Yes	No	No	No	No	N/A	No	N/A	No	No
Item #16	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Item #17	Yes	Yes	Yes	N/A	Yes	Yes	Yes	Yes	Yes	Yes	Yes	N/A	Yes	Yes	Yes	Yes
Item #18	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Item #19	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Item #20	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Internal Validity – confounding (selection bias)																
Item #21	N/A	Yes	No	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Yes	N/A	N/A	N/A
Item #22	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Yes	N/A	N/A	N/A
Item #23	No	N/A	No	No	No	No	No	No	N/A	Yes	No	N/A	No	Yes	No	Yes
Item #24	No	N/A	No	No	No	N/A	No	No	N/A	No	No	N/A	No	No	No	N/A
Item #25	No	Yes	N/A	N/A	N/A	N/A	No	No	N/A	N/A	Yes	N/A	No	N/A	N/A	N/A
Item #26	No	Yes	No	No	N/A	No	No	No	No	No	N/A	N/A	N/A	Yes	N/A	N/A
Power																
Item #27	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Yes	No	N/A	N/A	N/A	N/A	Yes	N/A	N/A